GEOTECHNICAL AND HYDROGEOLOGICAL FEATURES AND SPECIFIC SOLUTIONS FOR THE STRENGTHENING MEASURES IN THE CONSTRUCTION OF THE METRO IN SOFIA

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Abstract. The most essential part of the metro is its underground part, which is responsible for its transport advantage – conflict-free transport. It is its underground part that can create problems during implementation, as it must take into account the soil conditions, presence of groundwaters, impact of construction on the surrounding space – buildings and facilities, implementation technologies, isolations, earthquake behavior, durability of the facilities, method of operation, influence of the construction on the other modes of transport, ventilation and many, many other issues that should be solved and are solved in practice by the metro builders. Here we will mention some of the specific features that are characteristic of the city of Sofia and were solved during the study, implementation and operation of the three metro diameters of the Sofia Metro [1,2].

Keywords: soils, strengthening structures, monitoring, anchors, subsidence.

1. ENGINEERING-GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

In the first metro diameter, which connects the Obelya district and the Sofia Airport, especially in the section from the Obelya district to the Serdica 1 metro station, the metro has been studied with densely spaced profile borings, separately for the two tracks. For the needs of the design, summary tables have been compiled, and the soil types are grouped into 10 varieties. The studies were carried out by the then existing Department of Engineering Geology at SOFPROEKT. The first attempts with "in situ" tests were made with elastomer from TRANSPROEKT at the Serdica 1 metro station, at the request of University of Mining and Geology. The deformation modules and strength characteristics of the soils determined in this way are significantly higher than

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the previously determined values of these values through laboratory studies. This led to the correction of the strengthening structures of the ditches for the metro station from diaphragm walls, which, at a depth of the ditch of 15.30 m, instead of being supported on 4 levels, were supported on only two – at depths of 6 and 12 m below the terrain surface.

Research works for the extension of the metro after the metro station Serdica 1, as well as for the remaining two metro diameters, have already been diluted, but with a higher quality. When the data from these relatively sparse studies are supplemented with other data for the city of Sofia, they can already be sufficient [3,4].

To specify the strength and deformation properties of soils, observations are made and the results are processed through so-called "reverse calculations", i.e. search for such characteristics that correspond to the measured displacements of the geotechnical structures. The results of the reverse calculations are complemented with the results of studies using "field methods" – penetrometers and pressure gauges. It was found that the angles of internal friction of the soils, in the engineering geological studies, were underestimated by an average of 30%, and the cohesions – 3–4 times. All this affects the values of the active earth pressure and the passive resistance of the soils, and hence, the quantity and quality of the input materials, as well as the cost of construction [5].

What is the influence of the values of the angles of internal friction and cohesions on the values of the earth pressure and of the strengthening structures, can be seen from the presented two graphs, where standard excavation depths of 7 m are accepted – unsupported /console socle beam/ retaining structure of diaphragm walls and 12 m deep construction ditch of diaphragm wall, supported on three levels by anchors – figures 1 and 2.

All calculations and comparisons were made in the company GRUND 1 Ltd, according to methods given in [6].

The figures are conditional, as the prices of construction materials change dynamically. Much more accurate results can be indicated by comparisons of the bending moments in the structures obtained during the calculations, forces in the anchors and other static data, but in this case indicators have been chosen to indicate, albeit qualitatively, the great importance of the correct choice of the calculation parameters for the soil.

From the nature of the curves, it can be seen that the cohesions have the most essential importance for the parameters of the facilities. In this sense, the security coefficients, which at this stage are not yet regulated by law, should be reviewed. They are accepted as given in the Standards for the design of

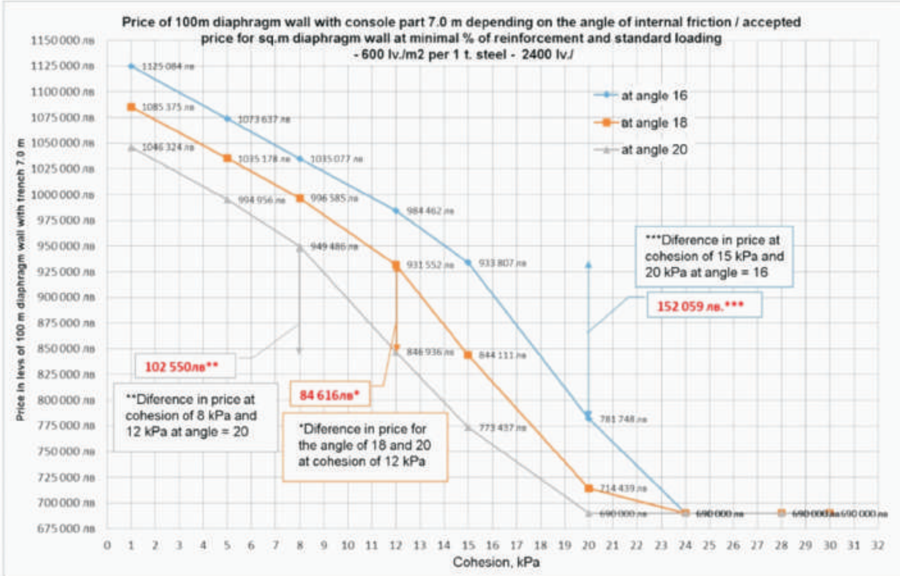

Fig. 1. Changes in the values of reinforcement of a console wall depending on the strength characteristics of the soils

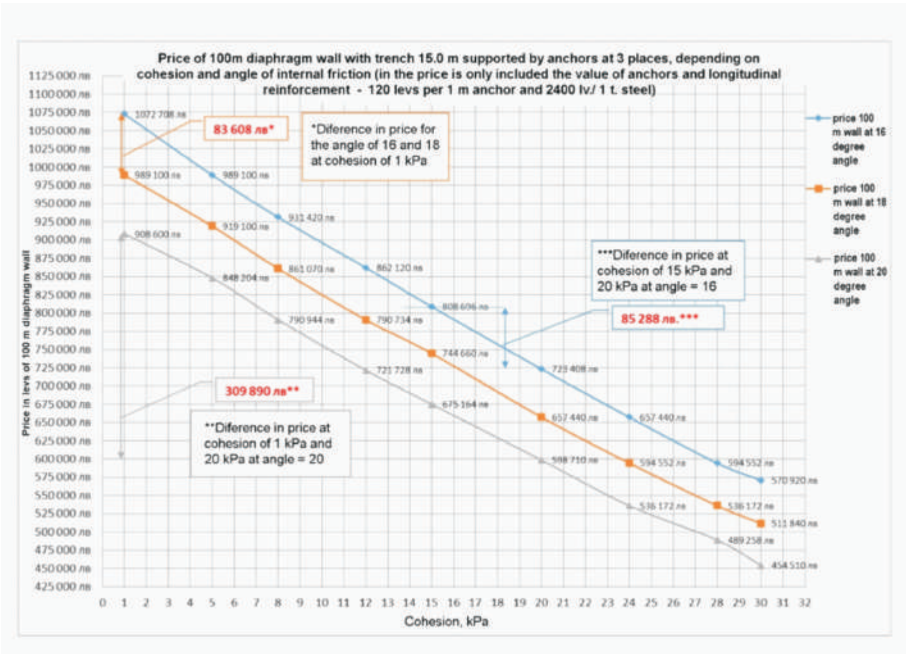

Fig. 2. Change in the values of a supporting wall depending on the strength characteristics of the soils

flat foundations and the Standards for the design of supporting walls, and conditionally they can be accepted as acceptable for the structures of the metro. According to EUROCODE 7 [7,8,9] the calculation characteristics are determined in another way specified in EUROCODE.

1.1. Directions for future activities in this area

It is mandatory to implement a monitoring, and the results of the analysis of the behavior of the structures to be used to correct the other types of studies;

When processing the results should be used the existing National Standards with safety factors, according to the type and responsibility of the facilities. For metro construction, safety factors should be used, adopted in the past years at a complex council in NISI, in the presence of specialists from the practice, teachers from universities, of the Sofia Metro and of the Ministry of Regional Development and Public Works.

Particular attention should be paid to clays of Pliocene origin. These soils are strong and water-tight. It is not yet resolved whether the active earth pressure should be determined as in soils that are below the water table, in dense Pliocene soils that are below the groundwater level.

An interesting decision was made by Prof. Bozhinov and Prof. Bratoev, in which part of the metro at the Interpred area has stepped on cinders and other waste, but with reinforced structure. No subsidence has been observed in this section for many years now. This gives grounds for a re-evaluation of the conditions necessary for the foundation of metro facilities. It can be assumed that there are some reserves in this regard.

2. GROUND WATERS

It was established that the ground water levels for the Sofia region are at depths of 8 to 10 m. In practice, drainage is carried out from the excavations themselves, as external drainage is practiced only at single sites, such as, for example, the excavations for the metro station at Orlov Most, where the ground water level is lowered to 10 m through eight external drainage wells. In all places, especially in the first metro diameter from Obelya district to the Center, the water lowering was carried out with drainage ditches /they are not even drainage/, passing on both sides of the bottom of the trenches.

In almost all cases of drainage of ditches, it was found that as the time of water extraction goes by, the aquifers are "depleted" and the water quantities decrease significantly.

The influence of ground water during deep excavations in sandy soils is particularly dangerous. The effects are several:

– during vibration compaction of water-saturated sands, especially those of Pliocene origin, liquefaction of the sands occurs and they now require additional processing. There were such cases at the metro station at Opalchenska Street, where the sand, as a result of vibrations, liquefied and additional drainage ditches were made to make an additional lowering of the water level. There was a similar case at the metro station next to the Paradise mall, where vibrating rollers were used to further compact the sand, as a result of which some of the sand was liquefied. In this aspect, it should be known that the Pliocene sands have a sufficiently high structural strength /crystalline strength/ and can easily bear the design loads without applying any firming works;

– in the presence of relatively clean sandy soils and at high levels of ground water, there is a danger of pushing the soil into the finished construction ditch, as a result of the so-called hydrodynamic pressure. Due to the danger of such an occurrence, at the metro station next to the monument of Father Paisiy of the third metro line, at an excavation depth of 25 m in almost clean sands and high levels of ground water that cannot be lowered with wells outside the fortification, at the bottom on the trench, according to the project of the company "GRUND1", a semi-permeable plug was implemented using the "Jet grouting" method. The plug was filled long before the excavation reached the critical bottom elevation (fig. 3).

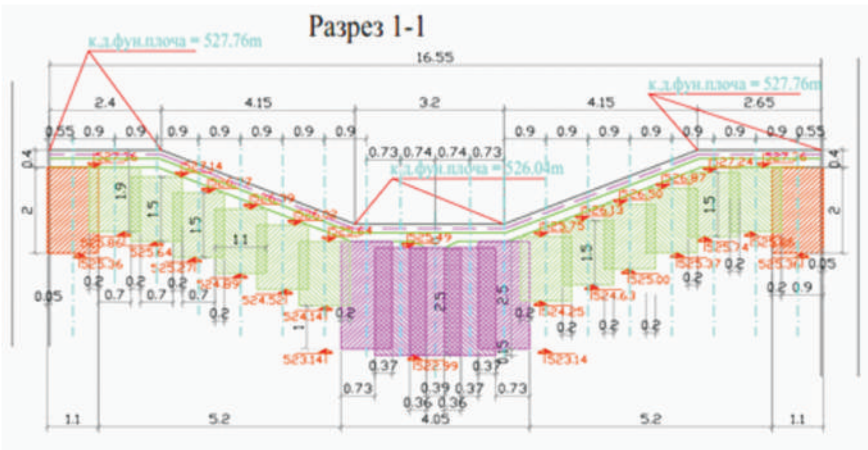

Fig. 3. Strengthening of the bottom of Metro Station 9 from the third metro diameter against hydrodynamic pressure

– when implementing anchors by drilling with a water jet in sands and especially under buildings, leakage of the sands through the drilling hole is observed. This causes a weakening of the ground foundation of the buildings and results in their additional subsidence.

In the observations so far, no additional subsidence of neighboring buildings due to water lowering has been detected. However, cases of subsidence in the presence of faults have been observed. Subsidences are minimal, but possible. An example of subsidence on a fault is the Central Military Club in Sofia, where it was necessary to further strengthen its earth foundation by means of injections.

No soil swelling was detected, with the exception of a small section of the first metro diameter, before the Serdica 1 station, where the bottom of the trench swelled by about one centimeter, due to the Pliocene origin of the soils and the long stay of the excavated section.

3. REINFORCING FENCES

At the beginning of metro construction, especially with the first metro diameter, drilled piles with large diameters – mainly 880 mm and diaphragm walls with a thickness of 80 cm – were used for reinforcing fences. The piles are implemented at axial distances of 1.0 to 1.20 m and, according to the depths of the excavations, are either cantilevered or supported. The diaphragm walls are implemented with jointed pipes and in normal cases they are supported. For the first metro diameter, the support was done by struts of pipes with large diameters – usually over 630 mm. They are placed one pipe per campada. Since the lengths of the campadas are 2.40 m each, the supports turned out to be dense and this was an obstacle when installing the formwork sheets. For this reason, an attempt was made to dilute the pipes through one, i.e. one pipe on two campadas. Obviously, one of the campadas remains unsupported, and the friction between the camps, as well as the arching of the active earth pressure, are used as support. In the tests with pipe cutouts, it was found that after the removal of the supports, the walls left without supports received displacements of 3 mm, which is evidence of lower earth pressure and efficiency of the connections between the campadas.

The initial calculations of the supporting walls used Bloom's method, where the passive earth pressure was mistakenly assumed to be a load. Conversely, it is the maximum resistance that the soil can bear under horizontal loads, i.e. a kind of "boundary resistance". For this reason, it is more correct to call it "passive soil resistance". The passive earth pressure is activated to its full value only when the structure undergoes a displacement of 5% of its embedded depth. This means that in order to activate the passive resistance of the soil when a part of the structure is embedded with a depth of 4 m, it must undergo a displacement of 20 cm – obviously this is not permissible, from which it immediately follows that the use of the passive resistance of soil is not only not true, but also not permissible. This has a negative effect especially on the cantilevered /unsupported/ walls, where the passive resistance of the soil is more important. Conversely, for the soil to move from a state of rest – $K_0 = 1 - \sin(\varphi)$, to active earth pressure, which is significantly lower – $K_a = \mathrm{tg}^2\left(45 - \dfrac{\varphi}{2}\right)$, it is necessary to move the support wall by only 1/500 to 1/1000 of its height, i.e., at an excavation depth of 10 m, a displacement of only 1-2 cm leads to a reduction in earth pressure, almost double. For these reasons, in ordinary engineering calculation methods, it is the load from active earth pressure that is applied, in contrast to some programs, where the calculations start with the load from earth pressure at rest – K_0 and then, depending on the obtained displacements, pass to active earth pressure – K_a. This is one of the reasons for the discrepancy between the results of the calculations and the results obtained from the monitoring of the completed supporting walls.

In 1983, a new method was created [10], in which, using the force-deformation method, the calculations of the strengthening structures were programmed, in which the resistance of the soil in the driven part was determined on the basis of Winkler. Then at the University of Mining and Geology, an EIM program was created, in which the calculations of the supporting fences are performed quickly and easily. This program was widely used by METRO-PROJECT to calculate the strengthening structures of many metro stations and linear excavations. This resulted in significant savings in terms of steel input, anchor lengths and thicknesses and types of supporting walls.

In more recent times, many other programs are used for the calculation of reinforcing structures: Tower, Plaxis, DC and many others.

During the implementation of the first diameter – the metro station at the National Stadium, as well as with the second and third metrodiameters, the support of the reinforcing structures is performed in different ways: by metal frames, by anchors, or the “top-down” method is used.

During the construction of the metro station next to the Lyulin – Center traffic tunnel with an excavation depth of 8.40 m, cantilevered (unsupported) nailed wide-flange steel profiles No. 55 were used to strengthen the walls of the excavations. This method turned out to be unsuccessful, first of all due to difficulties during the driving, and secondly, the cantilever piles received unacceptable displacements at their upper end – up to 14 cm.

In the latest implementations of reinforcing structures, due to the high levels of ground water, diaphragm walls are used, usually with a thickness of 60 cm. Where the depths of the excavations are smaller and there is no ground water, drilled piles or the so-called ”Berlin Walls” are used as supporting fences. They consist of driven steel profiles, usually anchored.

3.1. Passage of TBM through the front walls of launch and exit shafts and metro stations

In the usual works, in order to protect the openings in the diaphragm walls through which the TBM enters or departs the metro stations, or the launch and exit shafts from the intrusion of water and soil masses, methods were used to strengthen the soils in front of the openings, such as injections, jet grouting or in other ways. According to the design by GRUND 1 company, the front wall of the entrance shaft in the TBM entry area at Serdica 2 station, was reinforced with fiberglass rods. The implementation turned out to be successful and the TBM passed directly and without problems.

Again according to the design by the GRUND 1 company, during the implementation of an launch shaft of a third metro diameter, the diaphragm walls through which the TBM had to pass were reinforced only with fibers – engineer Simeon Popov is the designer. Such type of walls was also implemented at the exit shaft, but the fibers were made of plastic. There, even the reinforced concrete cushion of the TBM was successfully replaced only by fiber-reinforced concrete. Later, diaphragm walls with fibers were also borrowed by the company RICAT Ltd led by Eng. Antov Yanev at the metro stations Krasno Selo and the one at the corner of Bulgaria and Iv. Evst. Geshev boulevards [12]. It was found that this method needs further refinement.

4. SLOPES

In places where there are free spaces, trenches are formed with slopes. The slopes had the greatest application at the first metro diameter, from Obelya district to the center. In recent years, to strengthen the slopes were used driven steel rods, covered by fine mesh and shotcrete have been used to strengthen the slopes. In this way, depending on the characteristics of the soil there can be implemented vertical slopes with a height of up to 4-5 m and slopes of a grade up to 2:1 with a height of up to 12 m. There are such cases in the surrounding area of the metro station at Krasno Selo and at the launch shaft – the third metro diameter, where a slope with a height of 10 m, with a grade of 2:1, reinforced with steel rods and covered with mesh and shotcrete, has been standing for several years already.

5. SUPPORT STRUCTURES

In the case of the first metro diameter from Obelya district to the Center, the supporting structures were strengthened by steel pipes. At the tunnel to the Lyulin quarter, as well as at part of the metro station at National Stadium V. Levski, the top-down method was applied. The first anchors began to be applied during the continuation of the first metro diameter – from the Center to the airport, and this started from the metro station at National Stadium V. Levski – 22.5 m trench depth. At the beginning, the anchors were roped and tensioned up to 80% of their design load (according to DIN). Later, in parallel with the development of science and the accumulated experience, the anchors became "passive" /non-tensioned/ IBO type and this solution turned out to be more successful. Anchors were also used for sections of the second and third metro diameter. There were no cases of emergency situations when using anchored structures. When using passive anchors, the displacements of the upper edge of the walls rarely exceed 8-10 mm, which makes them safe for neighboring buildings and facilities. During more recent research by the company GRUND 1 it was established that in fact passive anchors are not only supporting structures, but they change the tense and deformed state of the massif behind the reinforcement. On this basis, in cohesive soils, the company uses shorter anchors that work without problems, for example, passive anchors with lengths of 10 m in cohesive soils and excavation depths of 12 to 18 m.

No problems occurred when using the top-down methods.

6. TUNNEL STRUCTURES

The first tunnel construction, in fact, a variant of the top-down method, was designed and executed at the tunnel to Lyulin quarter. The tunnel is 16 m deep, strengthened with piles with diameters of 880 mm. According to the project, it was planned to build the piles, then the roof slab. This is followed by excavation to a depth of 8 m, implementation of the intermediate slab and excavation to the ground elevation. After additional research, it was proved that the excavation could be done all the way to the bottom level, without the intermediate slab, and this option was executed, and the intermediate slab was executed afterwards. This proved above all that pile structures can withstand statically up to an excavated depth of 16 m, without intermediate support, but only supported at their upper end. The soils are sand, the soil water level is low. Data were obtained that, after the appropriate justification, fields of great height can be obtained between the supports, and that it is most effective to support the support structures as high as possible. Some data were also obtained on the actual type and distribution of active earth pressure.

The usual tunnel constructions are carried out in the so-called mining way. Such tunnels were built at the connection of the metro stations near the Hotel Hemus and at Hladilnika, during the extension of the third metro diameter, after the metro station at the Small City Theater, as well as in other places. A special achievement is the construction of the tunnel near the Sedrica 2 metro station /at TSUM/. This tunnel has a cross-section of 254 m^2 and the metro station was accommodated in it. The construction of this type of tunnel became necessary due to the requirement to preserve the antiquities of Ancient Serdika. The original design of the metro station was for it to occupy the entire space between the Central Market (TSUM) building and the buildings on the west side of the station. The implementation was planned to be done in an "open way" – strengthening with slotted walls of the entire perimeter to the bottom elevation, part of the open space to be occupied by the metro station, and the other part to be used as five-story underground garages. After a GPR survey, it was found that the entire area is full of antiquities of great historical value. For this reason, the station was narrowed, with one half with antiquities being opened for exhibition, and in order to preserve the other half in the area where the metro trains pass, and the metro station itself was completed in another way: at the entrance and exit of the metro station two shafts with dimensions of 24×25 m^2 were filled, and between the shafts, under the ancient ones, which are at depths of up to 7.5 m, the tunnel in question was filled, in which the entire metro station could fit. The antiquities were exhibited and this contributed to visualizing part of the history of Ancient Serdika. On the north side, the shaft had a depth of 24 m, and on the south side – 28 m. The great depths were necessary due to the need to pass the pipe of the second metrodiameter under the corresponding section of the first metrodiameter, which ran at a depth of 15.30 m. Over part of the antiquities, a "bridge structure" type coating was performed. - A variant of tunnelling is the so-called "tunnel boring machine" - TBM. The technology of implementation by the TPM method is known. Using this technology, parts of the first metro diameter were completed – between the stadium V. Levski and the Center, from the second metro diameter through the central part of the city and a large part of the third metro diameter – also through the densely built-up part of Sofia. The main advantage of the method is that the implementation is fast, it is not related to additional excavations and the tunnels can pass under buildings and facilities, preserving their integrity, and the implementation can be adapted to all soil, geological and hydrogeological conditions of the city. Sofia [1, 2]. The convenience of using these machines, which were used in Sofia, is that with them the settlement of the ground is in the amount of a few millimeters and this does not affect the buildings above them. While in the second and third metrodiameters the tunnels passed under streets, in the third metrodiameter the route passed under two buildings: at the Pette Kiosheta and under the building at the corner of Patriarh Evtimiy and Graf Ignatiev streets. In the first metro diameter, two tunnels with diameters of 5.80 m were used, through which the two metro lines passed separately. In the case of the second and third metro diameters, the diameters of the tunnels are 9.80 m, so that both metro lines can pass through one tunnel. The thickness of the tubing was 22 cm. In the two-way tunnels, the thickness of the tubing was greater and they proved to be sufficient to ensure the stability of the reinforcement. Measurements of the displacement of the tunnel linings, due to deformations of the rings, showed insignificant values – up to a few millimeters.

7. DEFORMATIONS OF THE TERRAIN ABOVE THE TUNNELS

This is a significant issue, as it is related to the preservation of the surrounding space, especially in relation to the subsidence of the adjacent buildings and facilities. In the previous executions with German-made TPM, the registered subsidence on the ground has an upper limit of 10–12 mm. When passing the TPM of the third metrodiameter, 1.40 m below the pipes of the first metrodiameter in the area of Orlov Most, to determine the settlement of the pipes of the first metrodiameter by Prof. Bozhinov and Prof. Bratoev, the scheme shown in Fig. 4 is used:

According to the scheme, the subsidence is due to soil loss, which is estimated to be about 0.2 to 0.3% of the cross-sectional area of the TPM. The measured values show the most common values around 0.2%, and if special conditions are observed – up to 1%. With a pipe diameter of 9.8 m, or 10 m round, the volume of the tunnel is 70 m^2. 0.1% of this volume is 0.07 m^2/m.

A dependence is used that the settlement triggers a soil wedge that has wall slopes relative to the principal vertical stress, which is assumed to be the geological load – $\left(45 - \dfrac{\varphi}{2}\right)$. In more recent studies, it turned out that in cohesive soils, the slopes of the boundary surfaces become steeper. The resulting slope has the shape of a cosine. For this reason, a coordinate system

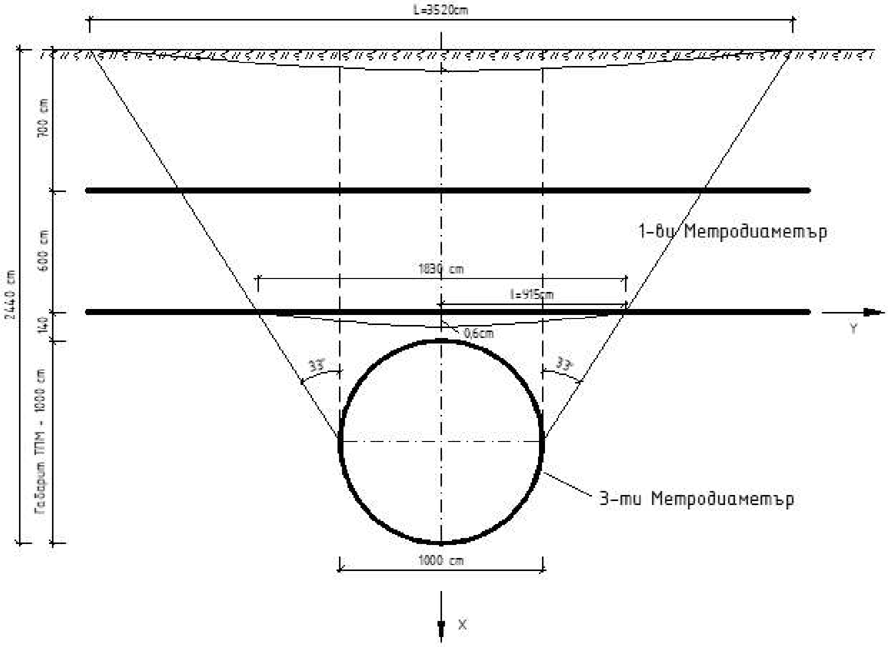

Fig. 4. Diagram of the passage of the pipes of the third metrodiameter under the pipes of the first metro diameter

is introduced with the origin – above the midpoint of the tube and the x-axis - pointing down, as shown in the drawing. A distribution function of the settlement diagram y is assumed:

$$y = b \times \cos \frac{\pi \times x}{2l}, \tag{1}$$

where, b is determined by the requirement that half the area of the subsidence diagram must be equal to half the volume of soil lost – due to the symmetry of the diagram. From the results obtained above, it is found that this volume is $0.07/2 \approx 0.035$ m^3/m. The length of the subsidence zone $L = 2.l$, provided that subsidence is sought at a height of 1.4 m above the TBM pipe, is determined by the equation:

$$\begin{aligned} L &= D + 2\left(1.4 + \frac{D}{2}\right) \times \operatorname{tg}\left(45 - \frac{\varphi}{2}\right) \\ &= 10 + 2\,(1.4 + 5) \times \operatorname{tg}\,(33) = 18.31 \text{ m}. \end{aligned} \tag{2}$$

The area of the subsidence diagram should be equal to the volume of soil lost:

$$0.035 = \int_0^{l=9.15} b \times \cos \frac{\pi \times x}{2 \times l} dx = b \times \int_0^{9.15} \cos \frac{\pi \times x}{2 \times 9.15} dx = 5.82 \times b. \quad (3)$$

From the solution, it is determined that the arrow of the cosine, which represents the settlement at a height of 1.4 m above the pipe, is $b = 0.035/5.82 = 0.006$ m = 6 mm.

The measured settlement of the pipe from the first metrodiameter is shown in Fig. 5. This is only 1.5 mm less than the predicted value.

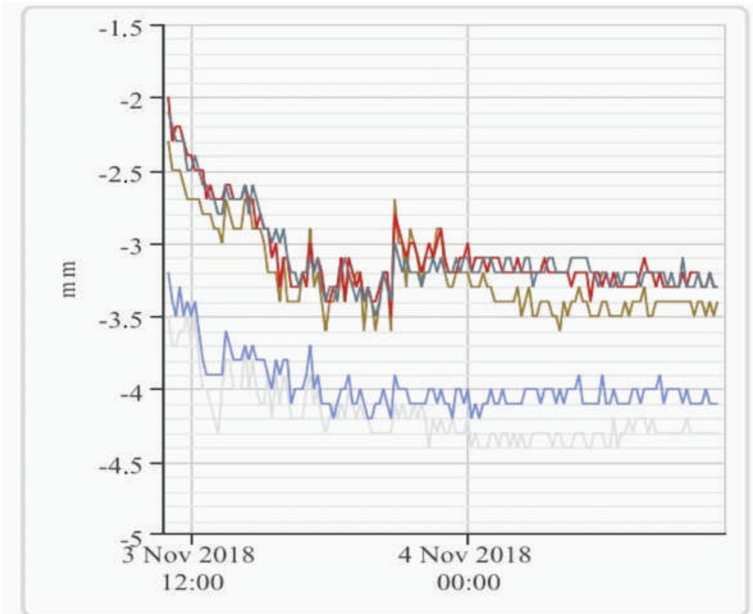

Fig. 5. Settlement of the pipes of the first diameter, due to the passage of the TBM at a depth of 1.40 m below them

In practice, it turned out that these calculations give acceptable results, and it is likely that they will be applied in the future, by changing the height of the soil wedge that is above the pipe. In these cases, it could be assumed that the soil loss could be higher, for example 0.2% of the total pipe volume.

When performing the tunnel constructions in a mining way, the results depend above all on the expected subsidence of the terrain when the tunnels are driven. According to the New Austrian Method, the settlements of the tunnel ceilings can be within 1–1.2 cm and these values are used to determine the settlements of the terrains or facilities above them. As with the tunnels executed by the New Austrian Method, as with the tunnels executed by means of TPM, monitoring is done not only of the settlement of the terrains above them, but also of the stressed state of the linings.

8. SURROUNDING SPACE

The influence of the subway on the surrounding space can be expressed in several directions:

8.1. Of the lowering of the water on the subsidence of the buildings in the range of the depression line of the water levels

To determine the lengths of the depression lines, Sichardt's formula is most often used. This formula is valid for constant water inflow, which is not quite true for the city of Sofia.

In practice in the city of Sofia, the radius of the depression curve varies from 25 to 120 m, depending on the filtration coefficients of the soils. In the case of sands, it is larger and reaches the upper limit, but because the sands are in separate lenses, the radii of the curves are up to 45–50 m. In the case of clay soils, subsidence depressions reach at most 4–6 m from the place of water lowering. With the Sofia soils, there is "depletion" of the aquifers and the water flow in the drainage facilities decreases sharply, already in the first 5–8 days after the beginning of the water lowering. The effect of this phenomenon is that the depression curve becomes steeper and the influence of the lowering of the water in the area of the depression line covers larger spaces.

In practice, the subsidence during water lowering – s, is calculated by a formula where the area of the stress diagram from an increase in the volumetric weight of the soil, due to the disappearance of the water rise at a depth h, is divided by the deformation modulus of the soil – E:

$$s = \frac{\gamma_w \times h^2}{2E} \tag{4}$$

A certain explanation of the weak influence of the water lowering on the subsidence of the adjacent terrains can best be explained by the high deformation modules of the Sofia soils.

When a building is founded on a fault, then uneven settlements occur on both sides of the fault. This necessitates a very careful study of the fault locations and additional strengthening of the soils, most often with the help of injections. An example of such subsidence is the Central Military Club in Sofia.

8.2. Impact due to relocation of the fortification fences

From the geodetic observations, it was established that in case of cantilever /unsupported/ fences made of drilling piles at depths of more than 7 m, displacements of the upper edge of the fences of 10 to 15 mm are obtained. With supported slotted walls, the displacements at the upper end of the walls are up to 8–12 mm. The most surprising thing is that with passive anchors, the displacements of the reinforcing fences are lower [13].

8.3. Influence of anchors on adjacent buildings

It has been proven that with the usual implementations of anchors, the conditions for stability and deformations of the buildings and the facilities above them are not violated. In some cases, when anchors are driven into sandy soils under water solution pressure, there is a flow of sand through the borehole, which can lead to additional settlement of buildings. This happened at one of the metro stations, where due to leakage of sand during the execution of the anchors, the building sank 3 cm without damage to the structure. When the conditions do not allow the implementation of anchors, shoring is done in one of the ways used in the implementation of the metro line 1 – from the "Obelya" quarter to the City Center. These are either tubes or frames sized to accommodate earth pressure. It has been proven by measurements that the load on the supporting structures in practice is much lower /even up to three times/ than specified in the designs, based on the soil parameters given in the research reports.

In conclusion, it can be said that so far, with all three metrodiameters, there is no violation of the surrounding space in any case.

9. MONITORING DURING IMPLEMENTATION

Monitoring during the implementation and operation of the metro constructions, /and all other constructions/ is an indicator of the accuracy of the calculations and at the same time gives grounds for changes, both in the soil indicators and in the static schemes of the structures.

According to the current practice, the monitoring consists of geodetic recording of the displacements of the structures, especially of the enclosing structures, placement of dynamometers on the anchors or struts, studies of the displacements of the retaining walls by means of built-in sensitive inclinometers in the slotted walls or piles, measurements of possible relocations of the terrain and adjacent buildings, as well as measurement of soil water levels and their flow rate. As additional activities that can be implemented in the future, there are sensors placed in the reinforcement of the slotted or sheet pile walls, the piles and even the steel profiles of the Berlin fences. Unfortunately, some of these activities are expensive and are often skimped on in the design and execution of underground structures. However, such measurements have been made, especially at the deep metro stations, as the beginning of the application of the inclinometers began with the implementation of the metro station at National Stadium Vasil Levski. Some of the results showed surprising discrepancies between the design and measured values of some quantities [13]. Some results of such measurements are shown below:

9.1. Measured values of bending moments and axial forces in tunnel linings in Germany

The diagrams are borrowed from the U-Bahn Referat and are shown in Fig. 6. The results are not from Bulgaria, but they are very indicative, which is why they are cited here [14].

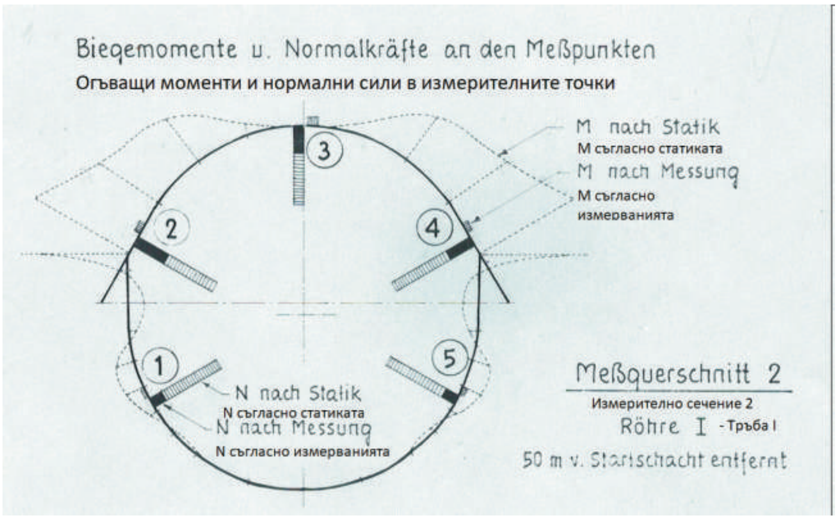

Fig. 6. Comparison between calculated and measured values of bending moments and compressive forces in the tunnel lining of a tunnel in Germany

The figure is copied directly from [14]. The German inscriptions have been preserved. The differences in the bending moments and bond forces in the completed cladding are shown. The results of the comparisons are simply stunning?! The differences may be due to wrong results for the soil characteristics, but also to errors in the adopted calculation scheme.

9.2. Almost all passive anchors of the IBO type remained unstressed after the execution of the excavations to the bottom elevation. At one of the sites with an excavation depth of 18 m, the largest additional stress on the anchors did not exceed 20–30 kN. An exception is the anchor support in the metro station near the church "St. Georgi" – third metrodiameter. There, 4 anchors with lengths of 30 m each and a total load of 1600 kN were designed on the slotted walls on one campa with a length of 2.40 m. They were replaced with two anchors of the same length /twice less/ and the installed dynamometers after excavation showed 150 kN per anchor - a total of 300 kN – 5 times less than the design value. More detailed information on monitoring results is given in [13].

9.3. The displacements of the unsupported /cantilever/ walls received displacements of up to 10–15 mm, and often times less. The movements of the supported walls are within 8–12 mm. Sometimes even less. This makes these constructions safe for the surrounding space.

9.4. Groundwater has variable flow rates depending on the respective section. After the start of water extraction, they significantly reduce their flow rate.

9.5. View of an inclinometer measurement made at the starting shaft of the metro station at the stadium Vasil Levski at an excavation depth of 22.5 m, is shown in Fig. 7.

When analyzing the results of another inclinometric measurement of a similar object with an excavation depth of 18 m, the following results were obtained /on the diagrams, the designations are in t and tm/:

10. COMPARISON OF RESULTS

By project:

The average load from earth pressure, determined by the Schnebely method is 88 kPa – the load from nearby buildings, as well as payload, is taken into account. The load from water pressure is additionally added.

Forces in the anchors – according to the attached scheme – from 318 kN to 471 kN – the anchors are passive IBO type with lengths of 10 m in the uppermost levels, up to 15 m in the free levels. Short anchors are imposed due to the proximity of buildings, under which anchors cannot be implemented.

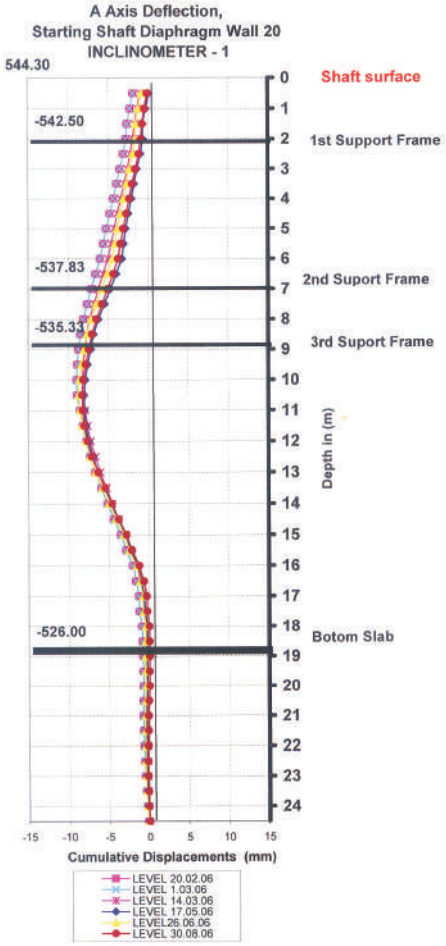

Fig. 7. Modification of the deformed state of a slotted wall during an excavation with a depth of 22.5 m at the National Stadium Vasil Levski

The maximum value of the bending moments is the bottom of the trench is 700 kNm. The values of the other bending moments are given in the figure, but in t and tm; Movement at the tread surface – 9 mm.

Driven part – 6 m.

Data obtained after processing the inclinometric curve:

Average load from earth pressure – about 3 times lower.

Anchor forces – up to 20 kN at most – about 20 times lower. Most anchors received no loading after excavation to ground elevation.

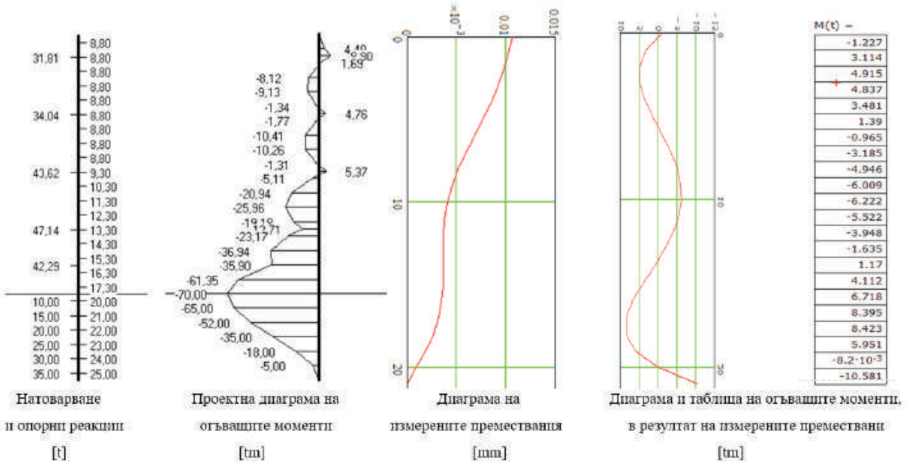

Fig. 8. Inclinometric measurement of a similar object with an excavation depth of 18 m

The maximum value of the bending moments is about 6 times lower than the design value determined according to the regulations?!

11. GENERAL CONCLUSIONS FROM THE MONITORING DATA

1. The earth pressure is usually much lower compared to the design values.
2. The bending moments with the supporting structures are also lower compared to the design values. Sometimes, the differences are significant.
3. Anchors are more effective when they are passive. They change the tense state of the space in front of the supporting structures. Movements with passive anchors are negligible. Anchor loads are negligibly low. Anchors are most effective when at higher elevations.
4. The passive resistance of the soils in the embedded part of the structures, determined by the Coulomb method, cannot be reached, due to the requirement for larger displacements. A new scheme given in [13] taking into account the contribution of cohesion, already during the formation of the earth pressure, shows that thanks to this scheme /correction of the Coulomb method/ the passive resistance of the connected soils can be many times higher and for smaller displacements. This also explains the relatively low values of embedment of the enclosing structures under the bottom of the construction trenches.

5. Movements of the supported structures are minimal - very rarely more than 10 mm. This applies both to ground displacements and to wall displacements due to bending.

From everything stated so far, it follows that during the construction of the subway in Sofia, the latest and newest methods were used for the study, design and implementation of subway constructions. However, there are additional outcomes that should be considered in the next stages of research and implementation of these constructs. Some of these questions are indicated in this report, others are also reflected in additional studies made in connection with the construction of the metro.

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